The GRB-Supernova Connection

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Abstract. Long-duration gamma-ray bursts (GRBs) are believed to be produced by the core collapse of massive stars and hence to be connected with supernovae (SNe). Indeed, for four pairs of GRBs and SNe, spectroscopically confirmed connection has been firmly established. For more than a dozen of GRBs the SN signature (the 'red bump') has been detected in the afterglow lightcurves. Based on the four pairs of GRBs and SNe with spectroscopically confirmed connection a tight correlation was found between the peak spectral energy of GRBs and the peak bolometric luminosity of the underlying SNe. The recent discovery of X-ray flash 080109 associated with a normal core-collapse SN 2008D confirmed this relation and extended the GRB-SN connection. Progress on the GRB-SN connection is briefly reviewed.

Keywords: Supernovae, X-ray sources, X-ray bursts, γ-ray sources, γ-ray bursts, Cosmology
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INTRODUCTION

Gamma-ray bursts (GRBs) are short and intense pulses of soft γ-rays and the brightest objects in the Universe. The key observed features of GRBs are as follows ([1, 2] and other review articles):

- The observed durations of GRBs are generally in the range 0.01–1000s.
- The spectra of GRBs are generally nonthermal, spanning a very broad band from radio to γ-ray.
- GRBs are characterized by a very large peak luminosity, 10^{50}–10^{53} erg s^{-1}.
- The total isotropic-equivalent energy emitted by a GRB in 1–10000 keV is 10^{50}–10^{54} erg, in the extremely energetic case comparable to the rest mass energy of Sun.
- The distribution of GRBs on the sky is isotropic.
- GRBs are at cosmological distances. At present the highest measured GRB redshift is $z = 6.29$, comparable to that of the remotest quasar.
- The large amount of energy, the non-thermal spectra, and the very short variability timescale of GRB lightcurves (can be as short as milliseconds) indicate that GRBs are relativistic: the outflow producing the GRB expands with a Lorentz factor > 100, in agreement with direct measurements [3].

GRBs are the most powerful explosion since the Big Bang. Since they are observable to very high redshift ($z > 10$), GRBs are very useful for probing cosmology.

GRBs are usually classified by their durations: those with durations smaller than 2 s are called short GRBs, and those with durations larger than 2 s are called long GRBs. This classification is purely empirical and very inaccurate, and sometimes ambiguity in classification may occur. The duration is defined in the observer frame and the duration distribution of the two classes significantly overlaps. Indeed, some GRBs with durations greater than 2 s have been argued to be of the same nature of short GRBs, e.g. GRBs 060505 and 060614 [4, 5].

It is generally thought that long GRBs are produced by the core collapse of massive stars [6]: the iron core of a rapidly spinning massive star (main sequence mass $> 30 M_\odot$) collapses to a black hole and an accretion disk forms around the black hole. Two oppositely directed jets, powered either by the disk accretion or the black hole's spin energy, produce the observed GRB. This collapsar model is supported by current observations: long GRBs are always found in star-forming galaxies, and some are found to be associated with core-collapse supernovae (SNe) [7].

In contrast, short GRBs are found in both star-forming and non-star-forming galaxies and are not associated with SNe [8]. They are thought to be produced by merger of two neutron stars or merger of a black hole and a neutron star.

Supernovae are stellar explosion at the end of a star's life. Electromagnetic emissions resulted from a SN event can last a very long time, from several years to centuries. The still bright Crab Nebula is the remnant of a SN that exploded

TABLE 1. Gamma-ray bursts and supernovae with spectroscopically confirmed connection ($H_0 = 72$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.28$, and $\Omega_\Lambda = 0.72$; see [13] for references)

GRB/SN	z^*	$E_{\gamma,\mathrm{peak}}{}^\dagger$	$E_{\gamma,\mathrm{iso}}{}^{**}$	$M_{\mathrm{SN,peak}}{}^\ddagger$	$E_K{}^\S$	$M_{\mathrm{ej}}{}^\P$	$M_{\mathrm{Nickel}}{}^\parallel$
980425/1998bw	0.0085	55 ± 21	0.00009 ± 0.00002	-18.65 ± 0.20	5.0 ± 0.5	10 ± 1	0.38–0.48
030329/2003dh	0.1687	79 ± 3	1.7 ± 0.2	-18.79 ± 0.23	4.0 ± 1.0	8 ± 2	0.25–0.45
031203/2003lw	0.1055	159 ± 51	0.009 ± 0.004	-18.92 ± 0.20	6.0 ± 1.0	13 ± 2	0.45–0.65
060218/2006aj	0.0335	4.9 ± 0.4	0.0059 ± 0.0003	-18.16 ± 0.20	0.2 ± 0.02	2 ± 0.2	0.2 ± 0.04

* Cosmic redshift.
† Peak energy of the integrated GRB spectrum in units of keV, measured in the GRB frame.
** Isotropic-equivalent energy of the GRB in units of 10^{52} erg, defined in the 1–10000 keV energy band in the GRB frame.
‡ Peak bolometric magnitude of the supernova, defined in the 3000–24000 Å wavelength band in the SN frame.
§ Explosion kinetic energy of the supernova in units of 10^{52} erg.
¶ Ejected mass in the supernova explosion in units of $M_\odot$.
$^\parallel$ Mass of ^{56}Ni produced by the SN explosion in units of $M_\odot$.

about a thousand years ago in the constellation of Taurus (~ 2 kpc from Earth).

The bulk of the SN electromagnetic emission is in the optical band, with a peak luminosity up to $\sim 10^{43}$ erg s^{-1}, intrinsically 10^{10} times brighter than Sun but 10^{10} times fainter than bright GRBs.

Most energy released by gravitational collapse of a progenitor star is carried away by gravitational waves and neutrinos ($\sim 10^{53}$ erg). A small part is converted by shock waves to the kinetic energy of the expanding fluid ($\sim 10^{51}$ erg), of which a fraction is emitted as electromagnetic radiation ($\sim 10^{49}$ erg) through radioactive decays.

SNe are usually nonrelativistic, with an expansion speed much smaller than the speed of light. In an extreme case (e.g., SN 1998bw), the expansion speed can reach $\sim 0.3c$. Because of the low luminosity of SNe relative to that of GRBs, usually SNe can only be observed to a noncosmological distance, and SNe discovered at $z > 1$ are rare [9].

In spite of the fact that observations of SNe have a much longer history than that of GRBs and hence our understanding of SNe is much better than that of GRBs, many important issues of SNe (e.g., the explosion mechanism) are still not solved [10].

SNe are classified by their spectra. SNe having hydrogen lines in their spectra are called Type II, otherwise called Type I. Type I SNe are further divided into three sub-classes. Type I SNe with silicon lines are called Type Ia. Type I SNe without silicon lines but with helium lines are called Type Ib. Type I SNe without silicon lines and without or with weak helium lines are called Type Ic.

SNe Ia, believed to be produced by thermal nuclear explosion of white dwarfs, are most luminous and often used as standard candles for measuring cosmological parameters. SNe Ibc and SNe II are generally thought to be produced by the core collapse of massive stars and are called core-collapse SNe.

THE GRB-SN CONNECTION

A surprising discovery in the past decade of GRB observations is that GRBs and SNe—two seemingly very different phenomena, with very different time durations, expansion velocities, and photon energy scales—are related.

On 25 April 1998, a faint GRB was detected by BeppoSax and BATSE, which has a smooth Fast-Rise-Exponentially-Decay (FRED) shape lightcurve with a duration ~ 35 s. About two and half days after the GRB, a bright SN 1998bw was discovered in the BeppoSax error box of the GRB [11]. The SN was one of the most unusual Type Ic SNe ever seen. It is very bright—comparable to a typical SN Ia—and has very strong radio emissions indicating relativistic expansion (the derived expansion speed $\sim 0.3c$ [12]). The small probability for a chance coincidence of GRB 980425 and SN 1998bw ($\sim 10^{-4}$) indicates that the two events are associated [11].

The host galaxy ESO184-G82 of this GRB has a very low redshift: $z = 0.0085$, which makes GRB 980425 the nearest GRB so far discovered with redshift. With this near distance, GRB 980425 is intrinsically at least 10^4 times fainter than cosmological GRBs.

Since GRB 980425/SN 1998bw, four pairs of GRBs-SNe with spectroscopically confirmed connection have been found, which are summarized in Table 1 (taken from [13]).

All the GRB-SNe are among a special subclass of SNe Ibc: broad-lined SNe, characterized by relative smooth spectra and a very large explosion energy. So they are often called ‘hypernovae’.

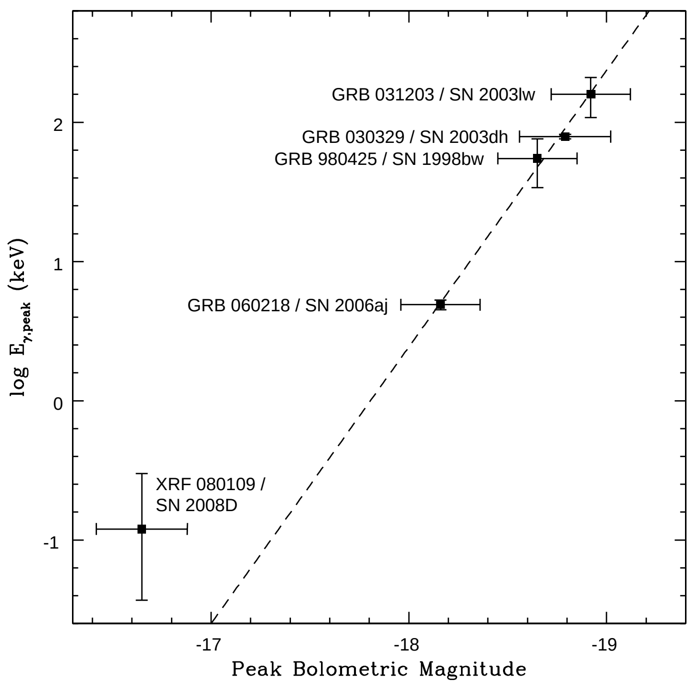

FIGURE 1. The peak spectral energy of GRBs/XRFs versus the peak bolometric magnitude of the underlying SNe (from [22]). The straight dashed line is the best fit to the four pairs of GRBs/SNe in Table 1, $\log E_{\gamma,\mathrm{peak}} = -35.38 - 1.987 M_{\mathrm{SN,peak}}$ (eq. 1).

GRB 060218 was detected by Swift. It is the second nearest GRB with redshift. The burst is very faint but has an extremely long duration (~ 2000 s). A SN associated with it, SN 2006aj, was discovered about three days after the GRB trigger. The XRT and UVOT onboard Swift started observing the GRB ~ 156 s after the trigger, so a very complete multi-wavelength observation on the event has been obtained [14, 15, 16]. The discovery of GRB 060218/SN 2006aj with high quality multi-wavelength spectra and lightcurve data put the GRB-SN connection on a solid foundation.

A remarkable blackbody component was discovered in the X-ray and UV-optical lightcurve of GRB 060218 (occupying 20% of the tocal emission and lasting up to 10000 s in the 0.3–10 keV X-ray emission), which was interpreted as SN shock breakout in the progenitor Wolf-Rayet star [14]. However, detailed calculations do not support the shock breakout interpretation [17].

Based on the observation of the four pairs of GRBs and SNe, a strong correlation between the GRB peak spectral energy ($E_{\gamma,\mathrm{peak}}$) and the SN maximum bolometric luminosity ($L_{\mathrm{SN,peak}}$; or equivalently, the mass of ^{56}Ni generated by the SN explosion, M_{Nickel}) was derived [13]

$$E_{\gamma,\mathrm{peak}} = 90.2\,\mathrm{keV}\left(\frac{L_{\mathrm{SN,peak}}}{10^{43}\mathrm{erg\,s^{-1}}}\right)^{4.97} . \tag{1}$$

Combination of this relation with the Amati relation [18] led to a constraint on the isotropic-equivalent energy of a GRB associated with a SN with a given maximum luminosity [13].

XRF 080109/SN 2008D

The $E_{\gamma,\mathrm{peak}}$–$L_{\mathrm{SN,peak}}$ relation in equation (1) was derived from four 'hypernovae' with GRBs. What does it imply if the relation is applied to a normal Type Ibc SN? This question was answered in [13] where it was inferred that "if normal Type Ibc SNe are accompanied by GRBs, the GRBs should be extremely underluminous in the gamma-ray band despite their close distances. Their peak spectral energy is expected to be in the soft X-ray and UV band, so they may be easier to detect with an X-ray or UV detector than with a gamma-ray detector." This 'prediction' seems to be confirmed by a recent discovery.

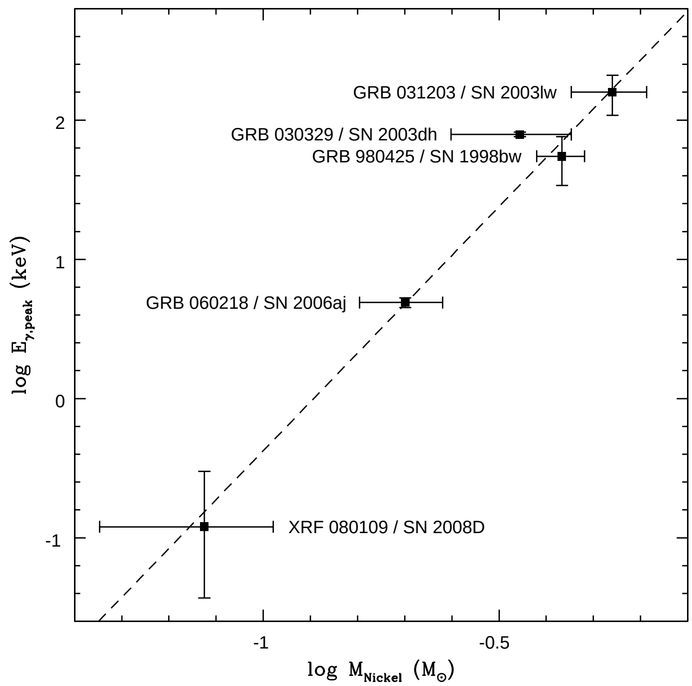

FIGURE 2. The peak spectral energy of GRBs/XRFs versus the mass of ^{56}Ni generated in the ejecta of the underlying SNe (from [22]). The straight dashed line is the best fit to the four pairs of GRBs/SNe in Table 1, $\log E_{\gamma,\mathrm{peak}} = 3.13 + 3.51 \log M_{\mathrm{Nickel}}$.

On 9 January 2008, a bright X-ray transient was discovered in spiral galaxy NGC 2770 during a follow-up observation of SN 2007uy in it by XRT/Swift. The transient has a FRED shape lightcurve and a duration ~ 600 s. Given the redshift $z = 0.006494$ of the galaxy, the average luminosity of the transient is $\approx 2 \times 10^{43}$ erg s^{-1}. At the same position of the X-ray transient, a Type Ib SN 2008D was found later [19, 20].

Although the nature of the transient is debatable, the most natural interpretation appears to be an X-ray flash (XRF)—the soft version of a GRB. Other interpretations (X-ray flare of a GRB, or SN shock breakout) do not look plausible [21, 22, 23].

The isotropic equivalent energy derived from an absorbed power-law fit of the XRT spectrum is 1.3×10^{46} erg in 1–10000 keV. A joint analysis on the XRT and UVOT data leads to a constraint on the peak spectral energy: 0.037 keV $< E_{\gamma,\mathrm{peak}} <$ 0.3 keV. With these results, XRF 080109 satisfies the Amati relation [22].

The peak of the SN lightcurve occurred at about 20 day after the explosion, with a peak bolometric magnitude ≈ -16.65 (corresponding to a maximum luminosity $\approx 1.4 \times 10^{42}$ erg s^{-1}). Fitting the lightcurve by an analytic model of SN emission powered by the radioactive decay of ^{56}Ni and ^{56}Co yielded a ^{56}Ni mass synthesized in the explosion between 0.05 and $0.1 M_{\odot}$ [19]. These results are in agreement with more sophisticated modeling [23, 24].

The above results, together with the $E_{\gamma,\mathrm{peak}}$ of XRF 080109 derived from the XRT and UVOT data, indicate that XRF 080109/SN 2008D agree with the $E_{\gamma,\mathrm{peak}}$–$L_{\mathrm{SN,peak}}$ relation (Fig. 1) and the $E_{\gamma,\mathrm{peak}}$–M_{Nickel} relation (Fig. 2) [22].

SN 2008D is a normal Type Ibc SN in terms of its luminosity and spectra, in contrast to other GRB-hypernovae. The detection of XRF 080109/SN 2008D extends the GRB-SN connection to normal core-collapse SNe. It may suggest that every Type Ibc (maybe Type II also) SN has a GRB/XRF associated with it. If this is true, events like XRF 080109 would occur at a rate comparable to that of SNe Ibc, $\sim 10^{-3}$ yr^{-1} in an average galaxy [25].

SPHERICAL GRBS

In the standard collapsar model of GRBs, collimation of the outflow is essential for avoiding baryon loading and producing a clean fireball with a Lorentz factor > 100. However, it appears that some GRBs/XRFs are spherical.

Investigations found that GRBs with softer spectra tend to have larger jet opening angles i.e. weakly collimated outflows (Fig. 3) [26, 13]. For GRBs/XRFs with $E_{\gamma,\mathrm{peak}} < 40$ keV (in the burst frame), the jet opening angle inferred

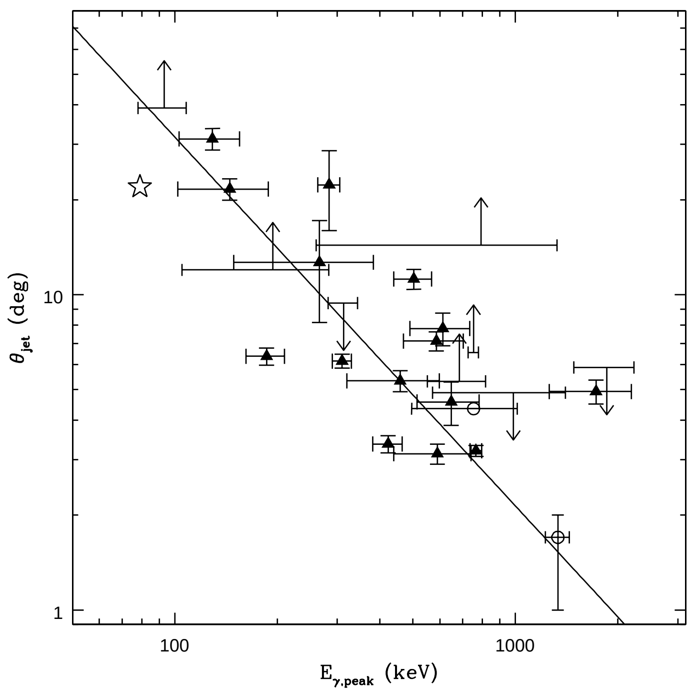

FIGURE 3. The jet opening angle of GRBs versus the peak energy of their spectra measured in the GRB frame (from [13]). The straight line is a maximum-likelihood fit to the data excluding the 8 GRBs with only limits, $\log\theta_{\rm jet} = 3.84 - 1.17 \log E_{\gamma,{\rm peak}}$.

from the above anti-correlation is so large that the burst outflow should be spherical [13]. This is consistent with radio observations on the soft XRF 020903, GRB 060218, and XRF 080109 [27, 16, 19].

Apparently, the standard internal/external-shock fireball model does not apply to GRBs/XRFs with a spherical outflow, since a spherical fireball outflow cannot avoid baryon loading efficiently: it must pass through the dense SN ejecta. Then, an unavoidable consequence of a spherical GRB/XRF is that the outflow producing the burst and the afterglow cannot have a very large Lorentz factor. Due to the loss of energy to the SN ejecta, the burst would also be very sub-energetic compared to normal GRBs.

Whether a spherical explosion can produce a GRB-like event is a question. The GRB fireball is trapped inside the heavy SN envelope so the energy of it may well be dissipated by the SN envelope without producing a GRB/XRF. However, two possible scenarios for producing a GRB/XRF from a spherical configuration can be imagined [22].

Scenario A. When a light fluid is accelerated into a heavy fluid, which is just the case of a spherical GRB explosion as outlined above, the Rayleigh-Taylor instability occurs. In a spherical GRB/SN explosion, the GRB fireball may emerge from the SN envelope through the Rayleigh-Taylor instability, then produce a GRB/XRF through either the internal-shock or the external-shock interaction.

Scenario B. The initial GRB fireball is killed by the SN envelope and the fireball energy is added to the SN explosion energy. A small fraction of the outer layer of the SN envelope is accelerated by the enhanced SN shock wave to a mildly relativistic velocity and generates a low-luminosity GRB/XRF via interaction with surrounding matter. This GRB-production mechanism through acceleration of the SN outer layer has been proposed for explaining the prompt emission of GRB 980425 [28]. Although this mechanism is able to account for the total X-ray energy emitted by XRF 080109, it is unable to explain GRB 060218 [22].

SUMMARY

So far, five pairs of nearby GRBs (or XRFs) and SNe with spectroscopically confirmed connection have been discovered: the four GRBs/SNe listed in Table 1, and XRF 080109/SN 2008D. There appears to be a relation between the GRB/XRF peak spectral energy and the SN peak luminosity (or the Nickel mass). The relation need be tested with future detection of GRB-SN and XRF-SN pairs.

Observing SN signatures in high-redshift GRBs is difficult, since by selection effects the observable GRBs at high redshift are bright and hence the underlying SNe are easily overshone by the GRB afterglows. In spite of this challenge, some GRBs have shown rebrightening and flattening in their late optical afterglows, which have been interpreted as emergence of the underlying SN lightcurve. A systematic study on the GRB afterglows with this approach suggests that all long GRBs are associated with SNe [29].

However, one must be cautious about the above conclusion, since alternative explanations for the rebrightening and flattening in the late optical afterglows of GRBs exist [30, 31].

In addition, some nearby long GRBs have not been found to have SNe in spite of extensive deep observations, including GRB 060505 and GRB 060614 [32, 33, 34]. Failed SNe have been predicted in theoretical study on the SN explosion and have been suggested to represent the main mechanism for producing cosmological GRBs ([35, 36], see however, [37]). Hence, it is possible that not every long GRB is associated with a SN.

On the other hand, although the discovery of XRF 080109 with SN 2008D may indicate that every SN Ibc has a preceding GRB or XRF-like event, it may also be true that not all core-collapse SNe are associated with GRBs/XRFs. For example, the broad-lined Type Ic SN 2003jd is only slightly less luminous than SN 1998bw but no GRB/XRF has been found to be with it [38, 39].

Searching for more pairs of GRBs (XRFs) and SNe in future observations is very important for understanding the nature of the GRB-SN connection, the nature of GRBs, and the explosion mechanism of core-collapse SNe.

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